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(54) Title: SYSTEM AND METHOD FOR SPECTRALLY EFFICIENT TRANSMISSION OF DIGITAL DATA OVER OPTICAL FIBER
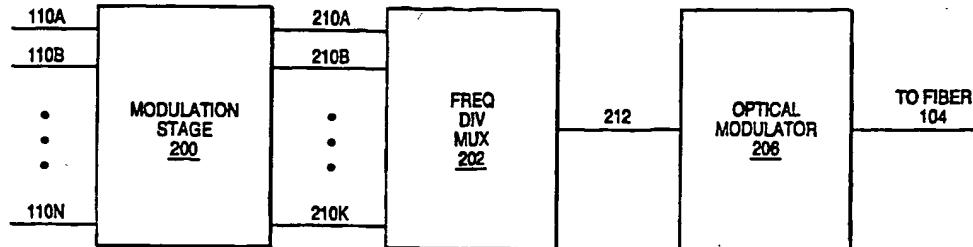
(57) Abstract

A system transmits digital data over an optical fiber at high aggregate data rates and high bandwidth efficiencies. The system includes a modulation stage, a frequency division multiplexer, and an optical modulator. The modulation stage QAM-modulates a plurality of incoming digital data channels. The frequency division multiplexer combines the QAM-modulated signals by frequency division multiplexing them into an RF signal. The optical modulator uses the RF signal to modulate an optical carrier for transmission over an optical fiber.

SYSTEM AND METHOD FOR SPECTRALLY EFFICIENT TRANSMISSION OF DIGITAL DATA OVER OPTICAL FIBER

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10   BACKGROUND OF THE INVENTION

1.   Field of the Invention

This invention relates generally to the transmission of digital data over optical fibers, and more particularly, to transmission based on quadrature amplitude modulation (QAM) and frequency division multiplexing.

15   2.   Description of the Related Art

As the result of continuous advances in technology, particularly in the areas of networking including the Internet, telecommunications, and application areas which rely on networking or telecommunications, there is an increasing demand for capacity for the transmission of digital data. For example, the transmission of digital data over a network's
20   trunk lines (such as the trunk lines for telephone companies or for the Internet), the transmission of images or video over the Internet, the distribution of software, the transfer of large amounts of data as might be required in transaction processing, or videoconferencing implemented over a public telephone network typically requires the high speed transmission of large amounts of digital data. Typical protocols which are intended to support such
25   transmissions include the OC, STM, and STS protocols. As applications such as the ones mentioned above become more prevalent, the use of these and similar protocols and the corresponding demand for transmission capacity will only increase.

Optical fiber is a transmission medium which is well-suited for the high speed transmission of digital data. Optical fiber has an inherent bandwidth which is much greater

than metal-based conductors, such as twisted pair or coaxial cable, and protocols such as the OC protocol have been developed for the transmission of digital data over optical fibers. However, increasing the data throughput of an optical fiber simply by increasing the clock speed of these protocols, such as moving from 155 million bits per second (Mbps) OC-3 to

5   625 Mbps OC-12, is not straightforward.

For example, existing optical fiber communication systems typically use simple modulation schemes which result in low bandwidth efficiencies of approximately 1 bit per sec per Herz (bps/Hz). As an example, the OC protocol is based on on-off keying (OOK), which is a bandwidth inefficient modulation scheme, and the transmission of OC signals across

10   optical fiber results in a bandwidth efficiency of approximately 1 bps/Hz. The useable bandwidth of current optical fibers is limited in part by dispersion and non-linearities which increase with bandwidth. The low bandwidth efficiency means that, for a given digital data rate, the transmitted signal will occupy a larger bandwidth. This results in larger dispersion and non-linear effects, which limit the useful transmission range of the system.

15   In addition, even if the optical fiber supports the higher data rates, the corresponding electronics and electro-optics might not be able to. For example, moving from OC-3 to OC-12 quadruples the bit rate but also requires the associated electronics to operate approximately four times faster. Electronics at these speeds simply may not be available or, if available, may have significant other drawbacks, such as larger power consumption, unwieldy size, high cost,

20   or unacceptable fragility.

In theory, the bandwidth efficiency problem could be addressed partly by the use of more bandwidth-efficient modulation schemes, such as quadrature amplitude modulation (QAM). These modulation schemes have been used previously in radio-wave and coaxial systems. However, optical fiber systems are based on an entirely different technology base

25   and many of the technologies, techniques, and design tradeoffs which were developed in order to implement more advanced modulation schemes in radio-wave and coaxial systems would have only minimal application to optical fiber systems. In addition, optical fiber systems present their own difficulties, such as fiber dispersion and non-linearities causing unwanted interference. Even if bandwidth-efficient modulation schemes could be easily applied to

30   optical fiber systems, their use does not fully address the high-speed electronics problem

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described above. For example, if OC data streams were QAM-modulated rather than OOK-modulated, a move from OC-3 to OC-12 would still require a four-fold increase in the speed of the corresponding electronics.

5   As a result, the application of sophisticated modulation schemes to optical fiber systems has been limited. For example, QAM has recently been applied to an optical fiber system for the transmission of compressed video for the cable TV industry. However, these communications systems run at low speeds with an aggregate data rate of less 1 billion bits per second (Gbps). Hence, they are not suited for high speed optical network operation.

10   Wavelength division multiplexing (WDM) is an alternate approach to increasing the data throughput of optical fiber systems. This approach, however, increases the aggregate bit rate simply by increasing the overall bandwidth utilized. It still suffers from bandwidth inefficiency. For example, a typical implementation of WDM might optically combine four OC-3 data streams, each at a different wavelength, to form an optical signal which has the same capacity as a single OC-12 data stream. The receiver would then optically separate the

15   four OC-3 data streams, based on their wavelengths. In this approach, however, each OC-3 still has a bandwidth efficiency of approximately 1 bps/Hz, so the wavelength division multiplexed signal will also have a bandwidth efficiency of no more than 1 bps/Hz.

       Thus, there is a need for systems and methods which transmit digital data over optical fibers at high aggregate data rates and with high bandwidth efficiencies, but without

20   unnecessarily increasing the speed requirements on the corresponding electronics.

SUMMARY OF THE INVENTION

       In accordance with the present invention, a system for transmitting digital data over an optical fiber includes a modulation stage, a frequency division multiplexer, and an optical modulator. The modulation stage receives a plurality of digital data channels and applies

25   QAM modulation to produce a plurality of QAM-modulated signals. The frequency division multiplexer combines the QAM-modulated signals by frequency division multiplexing them into an RF signal. The RF signal is input to the optical modulator, which generates an optical signal modulated by the RF signal, for transmission over an optical fiber.

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In a preferred embodiment, the modulation stage individually scrambles, forward error
encodes and then QAM modulates, using 64 QAM modulation, each of 64 incoming OC-3
digital data channels to produce 64 QAM-modulated signals. The frequency division
multiplexer combines the 64 resulting QAM-modulated signals in two steps, first frequency

5   division multiplexing the QAM-modulated signals eight signals at a time to produce a total of
eight signals at an intermediate frequency, and then frequency division multiplexing the eight
intermediate signals to produce the RF signal. The optical modulator includes an optical
source and an external modulator. The RF signal is applied to the external modulator to
modulate the optical carrier produced by the optical source. The resulting optical signal is

10   suitable for transmission across an optical fiber.

In accordance with another aspect of the invention, a system for receiving digital data
over an optical fiber includes a detector, a frequency division multiplexer, and a demodulation
stage. The detector detects the optical signal produced by the transmitter system described
previously, producing an RF signal. The frequency division demultiplexer separates the RF

15   signal into its constituent QAM-modulated signals by frequency division demultiplexing. The
demodulation stage converts the QAM-modulated signals into the original digital data
channels.

The present invention is particularly advantageous because the combination of QAM
modulation and frequency division multiplexing allows the transmission of digital data over

20   optical fibers at high aggregate data rates and with high bandwidth efficiencies while using
lower speed electronics. For example, the preferred embodiment described above has an
aggregate data rate of approximately 10 Gbps and a bandwidth efficiency of approximately 4
bps/Hz, but the associated electronics need only support the 155 Mbps OC-3 data rate rather
than the 10 Gbps aggregate rate.

25   BRIEF DESCRIPTION OF THE DRAWING

The invention has other advantages and features which will be more readily apparent
from the following detailed description of the invention and the appended claims, when taken
in conjunction with the accompanying drawing, in which:

FIG. 1 is a diagram of a system 100 in accordance with the present invention;

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FIG. 2 is a block diagram of one embodiment of the transmitter 102 of FIG. 1;

FIG. 3 is a block diagram of a preferred embodiment of the modulation stage 200 of FIG. 2;

FIG. 4 is a block diagram of a preferred embodiment of the modulation substage 300A of FIG. 3;

FIG. 5 is a block diagram of one embodiment of the frequency division multiplexer 202 of FIG. 2;

FIGS. 6A and 6B are block diagrams of a second embodiment of the frequency division multiplexer 202 of FIG. 2;

FIG. 7 is a block diagram of one embodiment of the receiver 106 of FIG. 1;

FIG. 8 is a block diagram of one embodiment of the frequency division demultiplexer 702 of FIG. 7;

FIGS. 9A and 9B are block diagrams of a second embodiment of the frequency division demultiplexer 702 of FIG. 7;

FIG. 10 is a block diagram of a preferred embodiment of the demodulation stage 704 of FIG. 7; and

FIG. 11 is a block diagram of a preferred embodiment of the demodulation substage 1000A of FIG. 10.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. 1 is a diagram of a system 100 in accordance with the present invention. The system 100 includes a transmitter 102, an optical fiber 104, and a receiver 106. The transmitter 102 is coupled to the receiver 106 by optical fiber 104.

The system 100 operates as follows. The transmitter 102 receives N digital data channels 110A-N (collectively, digital data channels 110) and combines them into a single optical signal for transmission over fiber 104. The transmitter 102 accomplishes this by using

a combination of quadrature amplitude modulation (QAM) and frequency division multiplexing (FDM). The optical signal created by transmitter 102 is transmitted across fiber 104 to receiver 106. Receiver 106 then reverses the functionality of transmitter 102, converting the optical signal into N digital data channels 120A-N.

5   In a preferred embodiment which shall be referred to as the "N = 64" or "K = 64" embodiment, the digital data channels 110 include 64 STS-3 channels, each providing digital data at a rate of 155 million bits per second (Mbps) for an aggregate rate of approximately 10 billion bits per second (Gbps). In addition, the use of QAM modulation typically results in a bandwidth efficiency in the range of 2-5 bps/Hz, which is a significant increase over the

10   typical 1 bps/Hz for conventional optical fiber systems; while the use of FDM allows the corresponding electronics to operate at 155 Mbps speeds, which is significantly lower than the 10 Gbps aggregate data rate. In alternate embodiments, the digital data channels 110 may be high speed channels which provide digital data at a predetermined, fixed rate, typically greater than 100 million bits per second (Mbps). For example, the digital data channels 110 may be

15   OC-3 or STM-1 channels. Other protocols may also be supported, including, for example, higher data rate channels such as OC-12, OC-48, etc. The number N of digital data channels 110 may also vary. For example, in a variant of the N = 64 embodiment, there are N = 128 digital data channels 110 for an aggregate bit rate of approximately 20 Gbps. Digital data channels 110 which are in optical form, such as OC-3, may be converted to electrical form by

20   an O/E converter stage coupled to the modulation stage 200.

        FIG. 2 is a block diagram of one embodiment of the transmitter 102 of FIG 1. The transmitter 102 includes a modulation stage 200, a frequency division multiplexer 202, and an optical modulator 204. These components form a data pipeline from the digital data channels 110 to the optical fiber 104. Specifically, the modulation stage 200 receives the digital data

25   channels 110. The modulation stage 200 is coupled to the frequency division multiplexer 202, which is coupled to the optical modulator 204. The optical modulator 204 transmits the optical signal to optical fiber 104.

        The transmitter 102 operates as follows. The modulation stage 200 receives the N digital data channels 110 and converts them into K QAM-modulated signals 210A-K.

30   Frequency division multiplexer 202 receives the QAM-modulated signals 210 and frequency

division multiplexes these signals into a single RF signal 212, which is then transmitted to the optical modulator 204. The optical modulator 204 produces an optical signal modulated by the RF signal and then transmits this resulting optical signal to optical fiber 104.

Various design tradeoffs are inherent in the design of a specific embodiment of
5   transmitter 102 for use in a particular application. For example, in QAM, the signal lattice is evenly spaced in complex signal space but the total number of states in the QAM constellation is a design parameter which may be varied. The carrier frequencies for the QAM-modulated signals 210 are also design parameters which may be varied. The optimal choices of number of states, carrier frequencies, and other design parameters for modulation stage 200 will
10 depend on the particular application. Some examples of modulation stage 200 will be described in further detail below. The frequency division multiplexer 202 also involves a number of design tradeoffs, such as the choices of intermediate frequencies, whether to implement components in the digital or in the analog domain, and whether to use multiple stages to achieve the multiplexing. As another example, an optical modulator 206 with better
15 linearity will reduce unwanted harmonics and interference, thus increasing the transmission range of transmitter 102. However, optical modulators with better linearity are also more difficult to design and to produce. Hence, the optimal linearity will depend on the particular application. An example of a system-level tradeoff is the allocation of signal power and gain between the various components. Accordingly, many aspects of the invention will be
20 described in the context of the $N = 64$ embodiment introduced earlier. However, it is to be understood that the invention is not limited to this specific embodiment.

FIG. 3 is a block diagram of a preferred embodiment of the modulation stage 200 of FIG. 2. The modulation stage 200 includes K modulation substages 300A-K. Each modulation substage 300 receives M of the digital data channels 110, where $M = N/K$, and
25 converts them into a single QAM-modulated signal 210. In this embodiment, the modulation substages 300 are identical. For clarity, FIG. 3 shows a detail of a single modulation substage 300A.

Modulation substage 300A includes M encoders 302A-M, a combiner 303, and a QAM modulator 304. Each of the encoders 302 is coupled to receive one of the digital data channels

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110. The QAM modulator 304 is coupled to the outputs of the encoders 302 via combiner 303.

The modulation substage 300A operates as follows. Each of the encoders 302 receives one of the digital data channels 110 and encodes the digital data. The encoded digital data

5   channels from the encoders 302 are received by combiner 303, which combines the M data streams into a single input for QAM modulator 304. QAM modulator 304 converts the received data stream into the QAM-modulated signal 210. Various types of encoding and QAM modulation schemes are possible, one of which will be discussed in FIG. 4.

In a preferred embodiment, encoder 302 includes a forward error correction (FEC)

10   encoder. This allows errors which occur during the subsequent processing stages and transmission to be corrected by the receiver. This is particularly relevant for optical fiber systems because they generally requires low bit error rates (BER) and any slight increase of the interference or noise level will cause the BER to exceed the threshold. FEC coding can compensate for these unwanted effects. Any variety of FEC techniques can be used,

15   depending on the system margin requirements. For short transmission distances, FEC coding may not result in any significant advantages.

FIG. 4 is a block diagram of the modulation substage 300A used in the N = 64 embodiment. In this embodiment, K = N = 64 and M = 1. In other words, there is one modulation substage 300 for each incoming digital data channel 110 and each individual

20   digital data channel 110 results in a separate QAM-modulated signal 210.

The modulation substage 300A includes a scrambler 400, a Reed-Solomon encoder 402, an interleaver 404, a trellis encoder 406, and QAM modulator 304. The scrambler 400, Reed-Solomon encoder 402, interleaver 404, and trellis encoder 406 are part of encoder 302. Combiner 303 of FIG. 3 is not required since M = 1. These components are coupled to form a

25   pipeline in which digital data flows from the scrambler 400 to the Reed-Solomon encoder 402 to the interleaver 404 to the trellis encoder 406 to QAM modulator 304, thus being converted from digital data channel 110 to QAM-modulated signal 210.

The modulation substage 300A operates as follows. The digital data channel 110 is received by scrambler 400 which scrambles the incoming digital data, thus randomizing the data string.

Reed-Solomon encoder 402 encodes the scrambled digital data channel according to a

5   Reed-Solomon code. Programmable Reed-Solomon codes are preferred for maintaining very low BER (typ. 10^{-12}) with low overhead (typ. less than 20%). For example, a Reed-Solomon code of (204,188) can be applied for an error correction capability of 8 error bits per every 188 data bits.

The interleaver 404 interleaves the digital data string output by the Reed-Solomon

10   encoder 402. The interleaving results in more robust error recovery due to the nature of trellis encoder 406. Specifically, FEC codes are able to correct only a limited number of mistakes in a given block of data, but convolutional encoders such as trellis encoder 406 tend to cluster errors together. Hence, without interleaving, a block of data which contained a large cluster of errors would be difficult to recover. However, with interleaving, the cluster of errors is

15   distributed over several blocks of data, each of which may be recovered by the FEC code. Convolution interleaving of depth 10 is preferred.

The trellis encoder 406 applies a QAM modulation, preferably 64 state QAM modulation, to the digital data stream output by the interleaver 404. The result typically is a complex baseband signal, representing the in-phase and quadrature (I and Q) components of

20   the eventual QAM-modulated signal 210. The use of 64 QAM yields a modulation bandwidth efficiency of 6 bps/Hz, thus increasing the overall transmission capacity by a significant factor over conventional OOK systems. QAM with a different number of states may be used and varying the number of states from 16 to 1024 will generally improve the modulation bandwidth efficiency by a factor of 4 to 10.

25   QAM modulator 304 typically uses the I and Q components to modulate a carrier, resulting in QAM modulated signal 210 characterized by a carrier frequency. In a preferred embodiment, QAM modulator 304 implements the QAM modulation digitally and the sampled QAM modulated signals 210 are then converted to the analog domain by A/D

converters for subsequent processing. In alternate embodiments, the QAM modulation may be implemented using analog techniques.

FIG. 5 is a block diagram of one embodiment of the frequency division multiplexer 202 of FIG. 2. The frequency division 202 includes K frequency shifters 500A-K and a

5   combiner 502. Various devices may be used as frequency shifters 500, including both analog and digital designs. A common design is based on mixing the incoming signal with a local oscillator and then selecting the component at the desired frequency by means of a frequency filter. Each of the frequency shifters 500 is coupled to receive one of the QAM-modulated signals 210. The combiner 502 is coupled to receive the outputs of the frequency shifters 500.

10   The frequency division multiplexer 202 operates as follows. Each frequency shifter 500 frequency shifts its incoming QAM-modulated signal 210 to a carrier frequency which is different from the carrier frequencies used by all the other frequency shifters 500. Hence, the output of the frequency shifters 500 is the QAM-modulated signals 210 but each at a different carrier frequency. The combiner 502 then combines these signals into the RF signal 212. In

15   other words, each QAM-modulated signal 210 is a different tone in the RF signal 212.

In a variant of the frequency division multiplexer 202 of FIG. 5, the modulation stage 200 may produce QAM-modulated signals 210 at carrier frequencies which are suitable for direct combination into RF signal 212. In this case, the frequency division multiplexer 202 does not require the frequency shifters 500 and combiner 502 directly combines the QAM-

20   modulated signals 210 into RF signal 212.

FIGS. 6A and 6B are block diagrams of a second embodiment of the frequency division multiplexer 202 of FIG. 2. In this approach, the frequency division multiplexing occurs in two stages: first stage 622 shown in FIG. 6A and second stage 624 shown in FIG. 6B. For convenience, the frequency division multiplexer 202 will be explained in reference to

25   the K = 64 embodiment.

In stage 622 of FIG. 6A, stage 622 is subdivided into the J substages 620A-J, with J = 8 in this embodiment. The 64 QAM-modulated signals 210 are also subdivided into J groups of H signals each, with J = H = 8 in this embodiment. Each substage 620 frequency division multiplexes one group of eight signals to form a single signal 607A-J, which is fed to the next

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stage 624. The processing of a single group of eight signals is shown in FIG. 6A. Other combinations of J and H may be used in alternate embodiments.

Substage 620A includes eight frequency shifters 604A-H, and a combiner 606. These components are coupled so that each incoming QAM-modulated signal 210 flows through a

5   frequency shifter 604 to combiner 606.

Substage 620A operate as follows. In this embodiment, the QAM-modulated signals 210 are frequency shifted by frequency shifter 604 to a first carrier frequency. At this point, the first carrier frequencies for each of the eight signals within a substage 620 is different, but each substage 620 uses the same set of eight carrier frequencies. For example, in a preferred

10   embodiment, the QAM-modulated signals 210 are frequency shifted to eight different carrier frequencies in the 1.0-1.6 GHz range. The combiner 606 combines the eight signals, all at different first carrier frequencies, into a single intermediate signal 607A which is input to stage 624 of FIG. 6B. Hence, at the output of stage 622 for the entire device, there are a total of eight intermediate signals 607, one for each substage 620. Furthermore, each intermediate

15   signal 607 contains eight tones, one for each of the incoming QAM-modulated signal 210 within the substage 620.

Stage 624 of FIG. 6B then repeats the function of stage 622 to form the RF signal 212. Specifically, the stage 624 includes eight frequency shifters 608A-J and a combiner 610, which are coupled in the same fashion as the frequency shifters 604 and combiner 606 of stage

20   622. Each frequency shifter 608 receives one of the intermediate signals 607 from the previous stage 622 and frequency shifts it to a second carrier frequency. Each frequency shifter 608 uses a different second carrier frequency so that there is no overlap between the various signals. For example, continuing the previous example, the intermediate signals 607 were in the 1.0-1.6 GHz range. Frequency shifter 608A may shift the intermediate signal

25   607A to the 0.4-1.0 GHz range, frequency shifter 608B to the 1.0-1.6 GHz range; frequency shifter 608C to the 1.6-2.2 GHz range, and so forth. Note that, in this example, shifter 608A down-shifts, shifter 608B is not required since no shift is necessary, and the other shifters 608C-J up-shift. The combiner 610 then combines these outputs into the RF signal 212, which occupies the spectral band from 0.4-5.2 GHz in this example.

Referring again to FIG. 2, the optical modulator 204 receives the RF signal 212 and produces an optical beam modulated by the RF signal 212. Various techniques may be used to achieve this function. In a preferred embodiment, the modulator 204 includes an optical source and an external optical modulator. Examples of optical sources include solid state

5   lasers and semiconductor lasers. Example external optical modulators include Mach Zehnder modulators, electro-optic modulators, and electro-absorptive modulators. The optical source produces an optical carrier, which is modulated by the RF signal 212 as the carrier passes through the external optical modulator. The RF signal may be predistorted in order to increase the linearity of the overall system.

10   Alternatively, the modulator 204 may be an internally modulated laser. In this case, the RF signal 212 drives the laser, the output of which will be an optical beam modulated by the RF signal.

Current optical fibers have two spectral regions which are commonly used for communications: the 1.3 and 1.55 micron regions. At a wavelength of 1.3 micron,

15   transmission of the optical signal is primarily limited by attenuation in the fiber 104; dispersion is less of a factor. Conversely, at a wavelength of 1.55 micron, the optical signal will experience more dispersion but less attenuation. Hence, the optical signal preferably has a wavelength either in the 1.3 micron region or the 1.55 micron region and, for long distance communications systems, the 1.55 micron region is generally preferred.

20   FIG. 7 is a block diagram of one embodiment of the receiver 106 of FIG. 1, which in large part, is the reverse of transmitter 102. The receiver 106 includes a detector 700 such as an avalanche photo-diode or PIN-diode, a frequency division demultiplexer 702, and a demodulation stage 704. These elements are coupled to form a data pipeline which transforms the optical signal from optical fiber 104 into the digital data channels 120. More specifically,

25   the detector 700 is coupled to the optical fiber 104; the frequency division demultiplexer 702 is coupled to the detector 700; and the demodulation stage 704 is coupled to the frequency division demultiplexer 702. The demodulation stage 704 outputs the digital data channels 120.

The receiver 106 operates as follows. The detector 700 detects the optical signal transmitted over optical fiber 104 to produce an RF signal 710, which includes K QAM-

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modulated signals 712A-K, each characterized by a different carrier frequency. Frequency division demultiplexer 702 frequency division demultiplexes the RF signal 710 into the K QAM-modulated signals 712. Demodulation stage 704 then converts the QAM-modulated signals 712 into the N digital data channels 120. This is essentially the reverse of transmitter

5   102, as shown in FIG. 2. RF signal 710, QAM-modulated signals 712, and digital data channels 120 are the counterparts to RF signal 212, QAM-modulated signals 210, and digital data channels 110.

FIG. 8 is a block diagram of one embodiment of the frequency division multiplexer 702 of FIG. 7. This embodiment includes a splitter 800, K frequency shifters 802A-K, and K

10 bandpass filters 804A-K. The splitter 800 is coupled to receive the RF signal 710 and each frequency shifter 802 is coupled to receive an output of splitter 800. The output of each frequency shifter 802 is coupled to an input of a bandpass filter 804.

The frequency division multiplexer 702 operates as follows. The splitter 800 splits the RF signal 710 into K signals, each of which is input into a frequency shifter 802 - bandpass

15 filter 804 combination. For example, one of the split RF signals is input into frequency shifter 802A. As described previously, the RF signal includes K different QAM-modulated signals each at a different carrier frequency. The frequency shifter 802A shifts the incoming RF signal by an amount such that one of these QAM-modulated signals is shifted to the pass band of filter 804A. This signal is filtered from the other signals by bandpass filter 804A, thus

20 producing QAM-modulated signal 712A. Each of the frequency shifters 802 shifts by a different frequency amount so that each bandpass filter 804 will select a different one of the K QAM-modulated signals contained in the RF signal 710. In a preferred embodiment, the pass bands of the filters 804A-K are the same so that QAM-modulated signals 712 are characterized by the same carrier frequency.

25 FIGS. 9A and 9B are block diagrams of a second embodiment of the frequency division multiplexer 702 of FIG. 7. This embodiment achieves the frequency division demultiplexing in multiple stages. FIG. 9A shows a first stage 920; while FIG. 9B shows second stages 922. The multi-stage frequency division demultiplexer 702 will be explained in the context of the K = 64 embodiment.

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In this embodiment, the first stage 920 of FIG. 9A includes a splitter 900, eight bandpass filters 902A-J and eight frequency shifters 904A-J. The splitter 900 splits the incoming RF signal 710 into eight signals, each of which is fed to a bandpass filter 902-frequency shifter 904 combination. As discussed in connection with FIGS. 6A and 6B, the RF

5   signal in this particular embodiment contains eight groups of eight signals each. The purpose of stage 920 is to frequency division demultiplex the RF signal 710 into the eight groups.

Stage 920 operates as follows. Each of the bandpass filters 902 has a different pass band and therefore selects a different one of the eight groups contained in RF signal 710. Continuing the example of FIGS. 6A and 6B, the various pass bands would be 0.4-1.0 GHz,

10   1.0-1.6 GHz, etc. The frequency shifters 904 then frequency shift each of these groups to the same carrier frequency, the 1.0-1.6 GHz band in this example. Since each group was originally characterized by a different carrier frequency, each of the frequency shifters 904 must frequency shift by a different amount. The output of stage 920 is eight signals 905A-J, each at the same carrier frequency and each containing one group of eight QAM-modulated

15   signals. Each of these signals is then input into stage 922 of FIG. 9B.

For convenience, FIG. 9B only shows the processing of signal 905A of the eight signals 905 from stage 920. Stage 922 of FIG. 9B includes a splitter 910, eight frequency shifters 912A-H, eight bandpass filters 914A-H, eight frequency shifters 916A-H, and eight A/D converters 918A-H. The incoming signal 905A contains eight QAM-modulated signals,

20   each at a different frequency. The splitter 910 splits the incoming signal into eight different signals, each of which will be converted to a digital QAM-modulated signal 712A-H.

This is accomplished as follows. Each of the frequency shifters 912 frequency shifts one of the QAM-modulated signals in the incoming signal to a common carrier frequency. Bandpass filters 914 filter out the signal at the common carrier frequency. As with FIG. 9A,

25   since each of the incoming signals is characterized by a different carrier frequency, each of the frequency shifters 912 must frequency shift by a different amount in order to shift the desired QAM-modulated signal to the proper bandpass region. Frequency shifter 916 then shifts these signals to a lower common carrier frequency. This is advantageous because bandpass filter 914 may operate at a higher frequency, permitting the use of filters with better performance.

A/D converters 918 sample the output of frequency shifters 916, converting the QAM-modulated signals from analog to digital form in preparation for digital QAM demodulation.

FIG. 10 is a block diagram of a preferred embodiment of the demodulation stage 704 of FIG. 7. The demodulation stage 704 includes K demodulation substages 1000A-K. FIG. 10 shows the details of one of these demodulation substages 1000A. Each demodulation substage 1000 converts one of the QAM-modulated signals 712 into M digital data channels 120A-M, where M = N/K. The demodulation substage 1000A includes a QAM demodulator 1002 coupled to M decoders 1004A-M by splitter 1003. The demodulation substage 1000A generally performs the reverse function of the modulation substage 300A. Specifically, the QAM demodulator 1002 removes the QAM modulation from the incoming QAM-modulated signal 712. Splitter 1003 separates the demodulated signals into its constituent M data streams, which are then decoded by decoders 1004 to form the digital data channels 120.

FIG. 11 is a block diagram of the demodulation substage 1000A of FIG. 10 used in the N = 64 embodiment. In this case, M = 1 so splitter 1003 is not required. Decoder 1004 includes trellis decoder 1100, de-interleaver 1102, Reed-Solomon decoder 1104 and descrambler 1106. These components are coupled in the reverse order of their counterparts shown in FIG. 4. Specifically, following the direction of data flow, the QAM demodulator 1002 is coupled to the trellis decoder 1100 to the de-interleaver 1102 to the Reed-Solomon decoder 1104 to the descrambler 1106.

The demodulation substage 1000A operates as FIG. 11 would suggest. The QAM demodulator 1002 demodulates the incoming QAM-modulated signal 712A, typically extracting baseband I and Q signals from the modulated carrier. Trellis decoder 1100 converts the I and Q signals to a digital stream. De-interleaver 1102 reverses the interleaving process. Reed-Solomon decoder 1104 reverses the Reed-Solomon encoding, correcting any errors which have occurred. Descrambler 1106 descrambles the resulting decoded signal to produce the digital data channels 120. The resulting digital data channels may be converted from electrical to optical form by a subsequent E/O conversion stage.

Although the invention has been described in considerable detail with reference to certain preferred embodiments thereof, other embodiments are possible. Therefore, the scope

of the appended claims should not be limited to the description of the preferred embodiments contained herein.

WHAT IS CLAIMED IS:

1.   A system for transmitting digital data over an optical fiber comprising:

a modulation stage for converting a plurality N of high-speed digital data channels into a plurality K of QAM-modulated signals, at least one of the digital data channels capable of transmitting digital data at a rate greater than 100 million bits per second;

a frequency division multiplexer coupled to the modulation stage for frequency division multiplexing the QAM-modulated signals into an RF signal; and

an optical modulator coupled to the frequency division multiplexer for producing an optical signal modulated by the RF signal, the optical signal suitable for transmission over an optical fiber.

2.   The system of claim 1 wherein:

at least one of the digital data channels is capable of transmitting digital data at a predetermined, fixed rate greater than 100 million bits per second.

3.   The system of claim 2 wherein:

at least one digital data channel is based on the OC protocol.

4.   The system of claim 2 wherein:

at least one digital data channel is based on the STM protocol.

5.   The system of claim 2 wherein:

at least one digital data channel is based on the STS protocol.

6.   The system of claim 1 wherein:

the plurality of digital data channels are capable of transmitting digital data at an aggregate rate greater than 2.5 billion bits per second.

7.   The system of claim 1 wherein the modulation stage includes:

a plurality K of modulation substages each modulation substage for converting M of the plurality of digital data channels into one of the plurality of QAM-modulated signals, with $M = N / K$.

8.   The system of claim 7 wherein each modulation substage further includes:

M encoders, each encoder for encoding one of the M digital data channels to form an encoded digital data channel; and

5   a QAM modulator coupled to the M encoders for converting the M encoded digital data channels into the QAM-modulated signal.

9.   The system of claim 8 wherein each encoder further includes:

a forward error correction encoder for encoding one of the M digital data channels according to a forward error correction code.

10   10.   The system of claim 8 wherein:

K = N and M = 1; and

each encoder includes:

a scrambler for scrambling one of the plurality of digital data channels,

a Reed-Solomon encoder coupled to the scrambler for encoding the scrambled

15   digital data channel according to a Reed-Solomon code,

an interleaver coupled to the Reed-Solomon encoder for interleaving the encoded digital data channel, and

a trellis encoder coupled to the interleaver for converting the interleaved digital data channel to a QAM constellation.

20   11.   The system of claim 1 wherein:

each QAM-modulated signal is characterized by a first carrier frequency, each of the first carrier frequencies different from the other first carrier frequencies; and

the frequency division multiplexer includes:

a combiner for combining the plurality of QAM-modulated signals into the RF

25   signal.

12.   The system of claim 1 wherein:

each QAM-modulated signal is characterized by a first carrier frequency, all of the first carrier frequencies the same; and

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the frequency division multiplexer includes:

a plurality of frequency shifters for frequency shifting the QAM-modulated signals from the first carrier frequencies to second carrier frequencies, each of the second carrier frequencies different from the other second carrier frequencies; and

a combiner for combining the plurality of QAM-modulated signals characterized by the second carrier frequencies into the RF signal.

13.   The system of claim 1 wherein the frequency division multiplexer comprises:

a multi-stage frequency division multiplexer.

14.   The system of claim 1 wherein the optical modulator comprises:

an internally modulated laser for producing an output optical beam modulated by the RF signal.

15.   The system of claim 1 wherein the optical modulator comprises:

an optical source for producing an optical carrier; and

an external optical modulator coupled to the optical source and the frequency division multiplexer for modulating the optical carrier with the RF signal.

16.   The system of claim 1 wherein:

the optical signal is characterized by a wavelength in the 1.3 micron region.

17.   The system of claim 1 wherein:

the optical signal is characterized by a wavelength in the 1.55 micron region.

18.   The system of claim 1 further comprising:

an O/E converter stage coupled to the modulation stage for converting the digital data channels from optical to electrical form.

19.   A system for receiving digital data over an optical fiber comprising:

a detector for detecting an optical signal transmitted over an optical fiber to produce an RF signal;

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a frequency division demultiplexer coupled to the detector for frequency division demultiplexing the RF signal into a plurality K of QAM-modulated signals; and

a demodulation stage for converting the plurality K of QAM-modulated signals into a plurality N of high-speed digital data channels, at least one of the digital data channels capable of transmitting digital data at a rate greater than 100 million bits per second.

20.   The system of claim 19 wherein:

at least one of the digital data channels is capable of transmitting digital data at a predetermined, fixed rate greater than 100 million bits per second.

21.   The system of claim 20 wherein:

at least one digital data channel is based on the OC protocol.

22.   The system of claim 20 wherein:

at least one digital data channel is based on the STM protocol.

23.   The system of claim 20 wherein:

at least one digital data channel is based on the STS protocol.

24.   The system of claim 19 wherein:

the plurality of digital data channels are capable of transmitting digital data at an aggregate rate greater than 2.5 billion bits per second.

25.   The system of claim 19 wherein:

the RF signal includes the plurality of QAM-modulated signals, each QAM-modulated signal characterized by a first carrier frequency, each of the first carrier frequencies different from the other first carrier frequencies; and

the frequency division multiplexer includes:

a splitter for splitting the RF signal into a plurality of RF signals,

a plurality of frequency shifters coupled to the splitter, each frequency shifter for frequency shifting one of the split RF signals from one of the first carrier frequencies to a second carrier frequency, all of the second carrier frequencies the same, and

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a plurality of bandpass filters coupled to the plurality of frequency shifters for filtering the split RF signals frequency shifted to the second carrier frequencies.

26.   The system of claim 19 wherein the frequency division demultiplexer comprises:

a multi-stage frequency division demultiplexer.

27.   The system of claim 19 wherein the demodulation stage includes:

a plurality K of demodulation substages each demodulation substage for converting one of the plurality of QAM-modulated signals into M of the plurality of digital data channels, with M = N / K.

28.   The system of claim 27 wherein each demodulation substage further includes:

a QAM demodulator for converting the QAM-modulated signal into M demodulated signals; and

M decoders coupled to the QAM demodulator, each decoder for decoding one of the M demodulated signals to form a digital data channel.

29.   The system of claim 28 wherein:

the RF signal includes the plurality of QAM-modulated signals, each QAM-modulated signal characterized by a first carrier frequency, each of the first carrier frequencies different from the other first carrier frequencies; and

each QAM demodulator is further for converting the QAM-modulated signals characterized by the first carrier frequencies into the M demodulated signals.

30.   The system of claim 28 wherein each decoder further includes:

a forward error correction decoder for decoding one of the M demodulated signals according to a forward error correction code.

31.   The system of claim 28 wherein:

K = N and M = 1; and

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each decoder includes:

a trellis decoder coupled to the QAM demodulator for decoding the demodulated signal according to a QAM constellation,

a de-interleaver coupled to the trellis decoder for de-interleaving the decoded

5   signal,

a Reed-Solomon decoder coupled to the de-interleaver for decoding the de-interleaved signal according to a Reed-Solomon code; and

a descrambler coupled to the Reed-Solomon decoder for descrambling the decoded signal.

10   32.   The system of claim 19 further comprising:

an E/O conversion stage coupled to the demodulation stage for converting the digital data channels from electrical to optical form.

33.   A method for transmitting digital data over an optical fiber comprising:

receiving a plurality N of digital data channels, at least one of the digital data

15   channels capable of transmitting digital data at a rate greater than 100 million bits per second;

converting the plurality of digital data channels into a plurality K of QAM-modulated signals;

frequency division multiplexing the QAM-modulated signals into an RF signal; and

20   producing an optical signal modulated by the RF signal, the optical signal suitable for transmission over an optical fiber.

34.   The method of claim 33 wherein:

receiving the plurality of digital data channels includes receiving the digital data channels at a predetermined, fixed rate.

25   35.   The method of claim 34 wherein:

at least one digital data channel is based on the OC protocol.

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36.   The method of claim 34 wherein:

at least one digital data channel is based on the STM protocol.

37.   The method of claim 34 wherein:

at least one digital data channel is based on the STS protocol.

5   38.   The method of claim 33 wherein:

receiving the plurality of digital data channels includes receiving the plurality

of digital data channels at an aggregate rate greater than 2.5 billion bits per second.

39.   The method of claim 33 wherein converting the plurality N of digital

data channels into the plurality K of QAM-modulated signals includes:

10   for K times in parallel, converting M of the plurality of digital data channels

into one of the plurality of QAM-modulated signals, with M = N / K.

40.   The method of claim 39 wherein converting M of the plurality of digital

data channels into one of the plurality of QAM-modulated signals includes:

in parallel, encoding each of the M digital data channels to form an encoded

15   digital data channel; and

converting the M encoded digital data channels into the QAM-modulated

signal.

41.   The method of claim 40 wherein encoding each of the M digital data

channels includes:

20   encoding each of the M digital data channels according to a forward error

correction code.

42.   The method of claim 40 wherein:

K = N and M = 1; and

encoding each of the M digital data channels to form an encoded digital data

25   channel includes:

scrambling the digital data channel,

encoding the scrambled digital data channel according to a Reed-Solomon code;

interleaving the encoded digital data channel, and

applying a QAM modulation to the interleaved digital data channels.

43.   The method of claim 33 wherein:

each QAM-modulated signal is characterized by a first carrier frequency, each of the first carrier frequencies different from the other first carrier frequencies; and

frequency division multiplexing the QAM-modulated signals into the RF signal includes:

combining the plurality of QAM-modulated signals into the RF signal.

44.   The method of claim 33 wherein:

each QAM-modulated signal is characterized by a first carrier frequency, all of the first carrier frequencies the same; and

frequency division multiplexing the QAM-modulated signals into the RF signal includes:

frequency shifting the QAM-modulated signals from the first carrier frequencies to second carrier frequencies, each of the second carrier frequencies different from the other second carrier frequencies; and

combining the plurality of QAM-modulated signals characterized by the second carrier frequencies into the RF signal.

45.   The method of claim 33 wherein frequency division multiplexing the QAM-modulated signals into an RF signal comprises:

frequency division multiplexing the QAM-modulated signals in at least two stages.

46.   The method of claim 33 wherein producing the optical signal modulated by the RF signal comprises:

producing an optical carrier; and

modulating the optical carrier with the RF signal.

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47.   The method of claim 33 wherein:

the optical signal is characterized by a wavelength in the 1.3 micron region.

48.   The method of claim 33 wherein:

the optical signal is characterized by a wavelength in the 1.55 micron region.

5   49.   The method of claim 33 further comprising:

converting the digital data channels from optical to electrical form.

50.   A method for receiving digital data over an optical fiber comprising:

detecting an optical signal transmitted over an optical fiber to produce an RF

signal;

10   frequency division demultiplexing the RF signal into a plurality K of QAM-

modulated signals; and

converting the plurality K of QAM-modulated signals into a plurality N of

digital data channels, at least one of the digital data channels capable of transmitting digital

data at a rate greater than 100 million bits per second.

15   51.   The method of claim 50 wherein:

the digital data channels transmit digital data at a predetermined, fixed rate.

52.   The method of claim 51 wherein:

at least one digital data channel is based on the OC protocol.

53.   The method of claim 51 wherein:

20   at least one digital data channel is based on the STM protocol.

54.   The method of claim 51 wherein:

at least one digital data channel is based on the STS protocol.

55.   The method of claim 50 wherein:

the plurality of digital data channels transmit digital data at an aggregate rate

25   greater than 2.5 billion bits per second.

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56.   The method of claim 50 wherein:

the RF signal includes the plurality of QAM-modulated signals, each QAM-modulated signal characterized by a first carrier frequency, each of the first carrier frequencies different from the other first carrier frequencies; and

5   frequency division demultiplexing the RF signal includes:

splitting the RF signal into a plurality of RF signals,

frequency shifting the split RF signals from the first carrier frequencies to second carrier frequencies, all of the second carrier frequencies the same, and

bandpass filtering the split RF signals frequency shifted to the second carrier

10   frequencies.

57.   The method of claim 50 wherein frequency division demultiplexing the RF signal comprises:

frequency division demultiplexing the RF signal in multiple stages.

58.   The method of claim 50 wherein converting the plurality K of QAM-

15   modulated signals into a plurality N of digital data channels includes:

for K times in parallel, converting one of the plurality of QAM-modulated signals into M of the plurality of digital data channels, with M = N / K.

59.   The method of claim 58 wherein converting one of the plurality of QAM-modulated signals into M of the plurality of digital data channels includes:

20   converting the QAM-modulated signal into M demodulated signals; and

decoding each of the M demodulated signals to form the digital data channels.

60.   The method of claim 59 wherein:

the RF signal includes the plurality of QAM-modulated signals, each QAM-modulated signal characterized by a first carrier frequency, each of the first carrier frequencies

25   different from the other first carrier frequencies; and

converting the QAM-modulated signal into M demodulated signals includes converting the QAM-modulated signal characterized by the first carrier frequency into the M demodulated signals.

61.   The method of claim 59 wherein decoding each of the M demodulated signals includes:

decoding the demodulated signal according to a forward error correction code.

62.   The method of claim 59 wherein:

$K = N$ and $M = 1$; and

decoding each of the M demodulated signals includes:

decoding the demodulated signal according to a QAM constellation,

de-interleaving the decoded signal,

decoding the de-interleaved signal according to a Reed-Solomon code; and

descrambling the decoded signal.

63.   The method of claim 50 further comprising:

converting the digital data channels from electrical to optical form.

FIG. 1
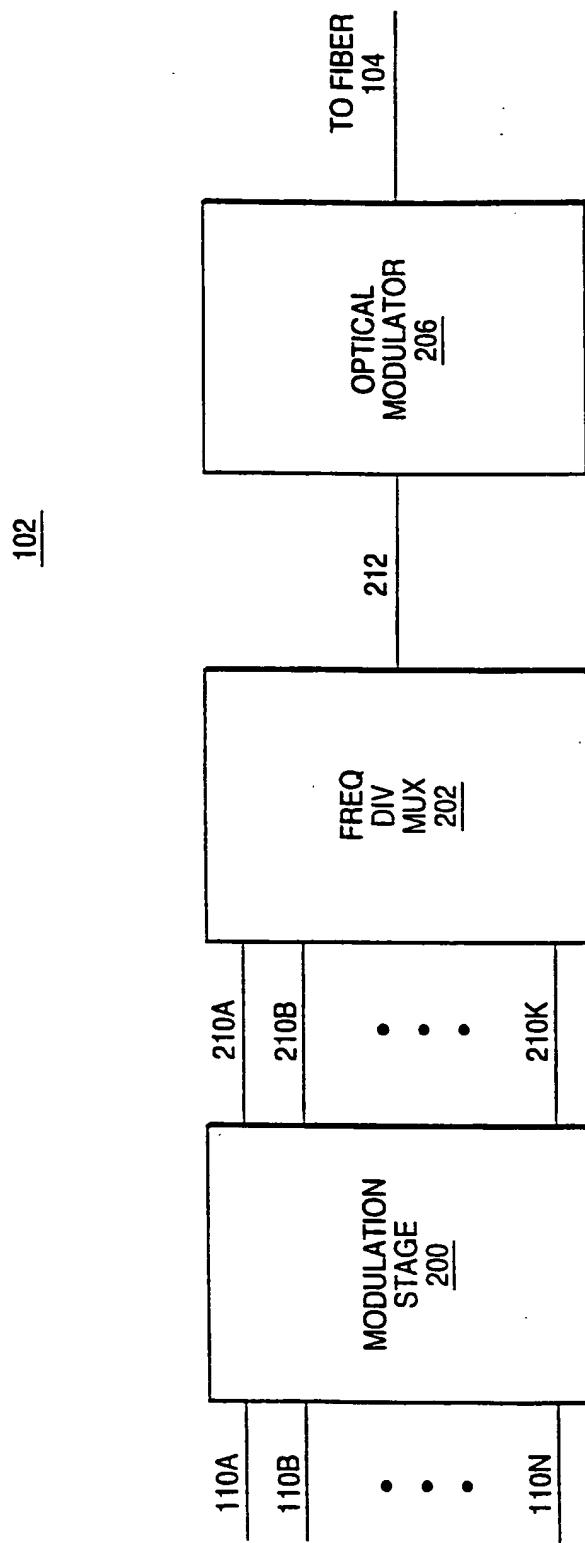
FIG. 2

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200
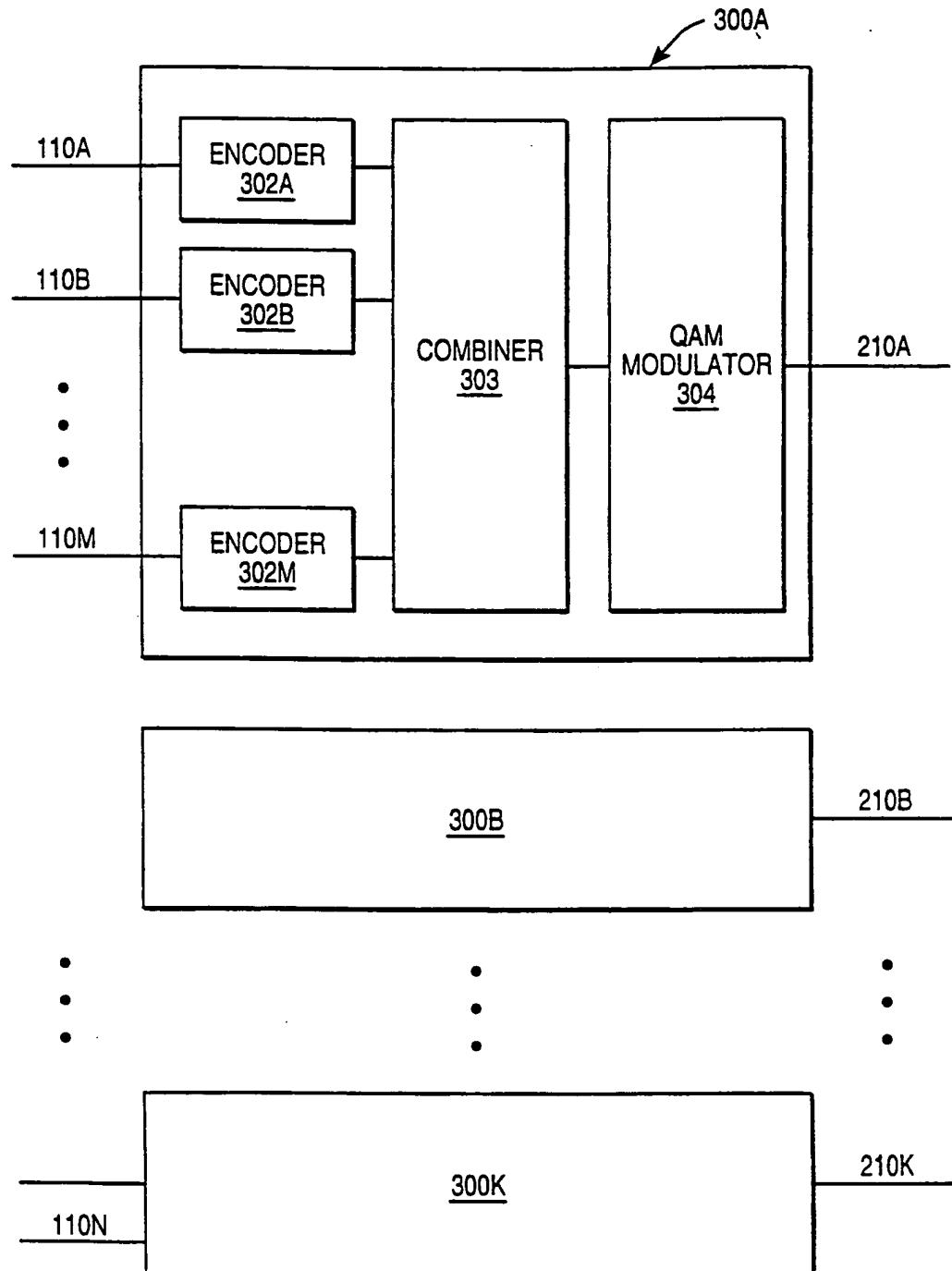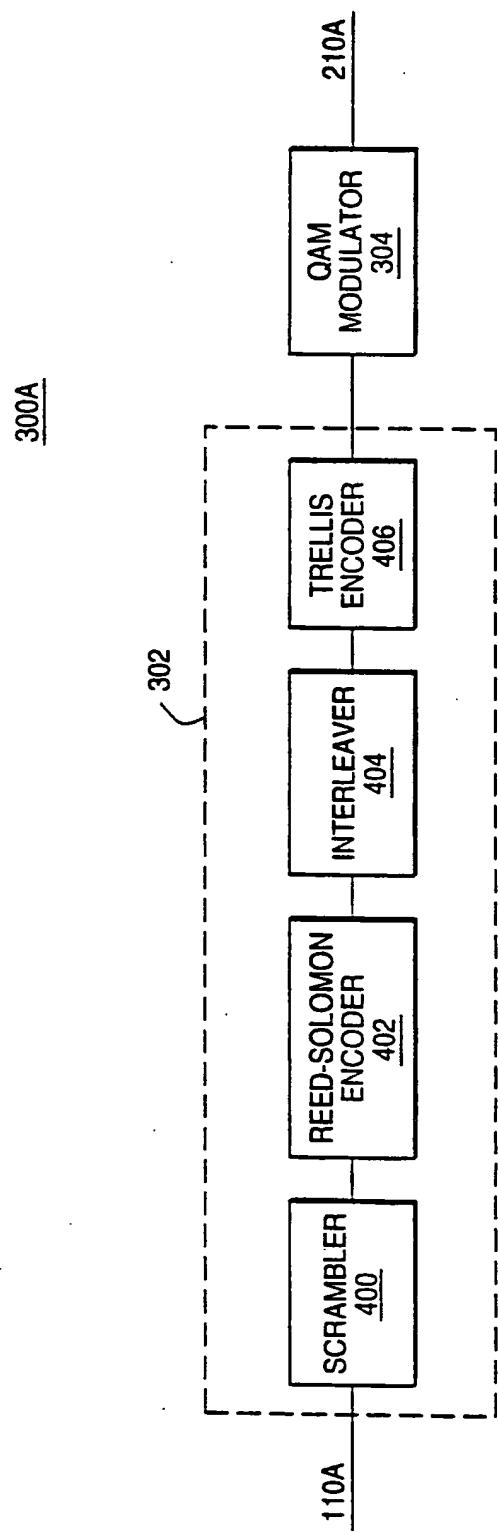
300A

ENCODER
302A

110A

ENCODER
302B

110B

COMBINER
303

QAM
MODULATOR
304

210A

ENCODER
302M

110M

300B

210B

300K

210K

110N

FIG. 3

FIG. 4

FIG. 5

622

FIG. 6A

FIG. 6B

FIG. 7

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FIG. 8

920
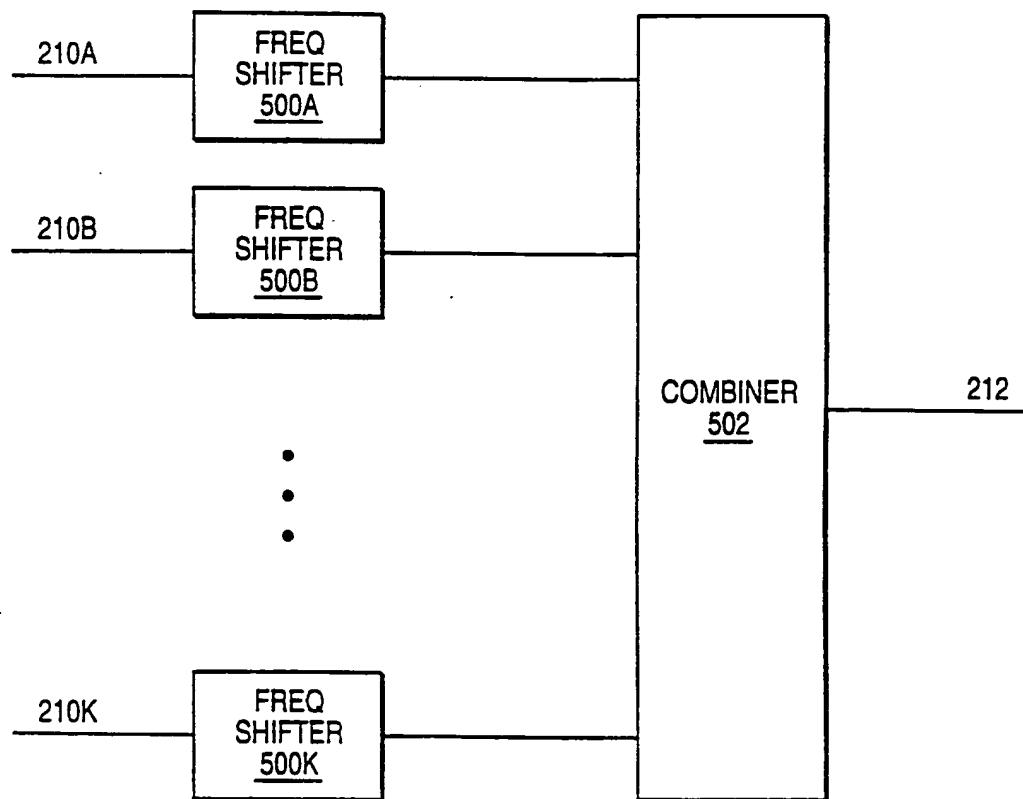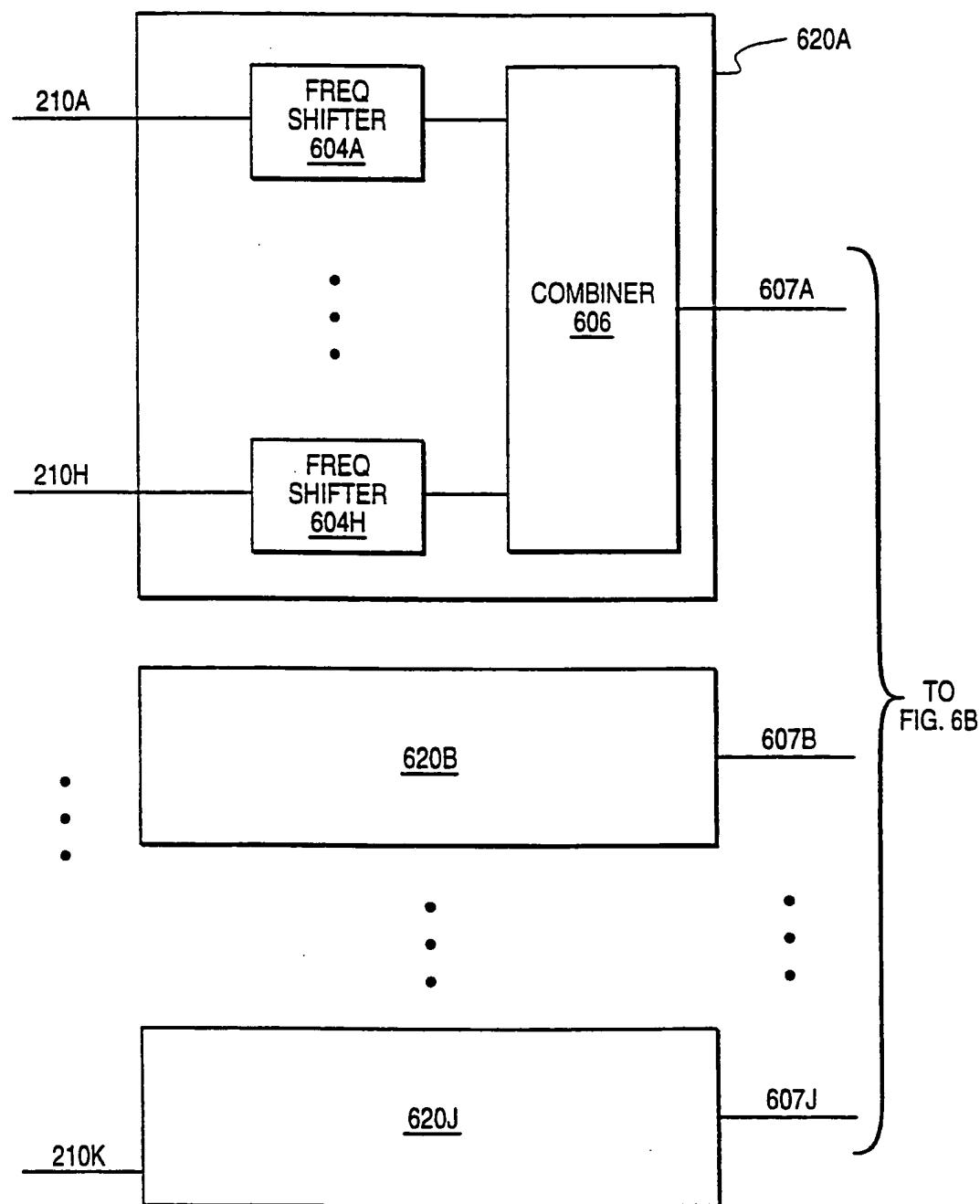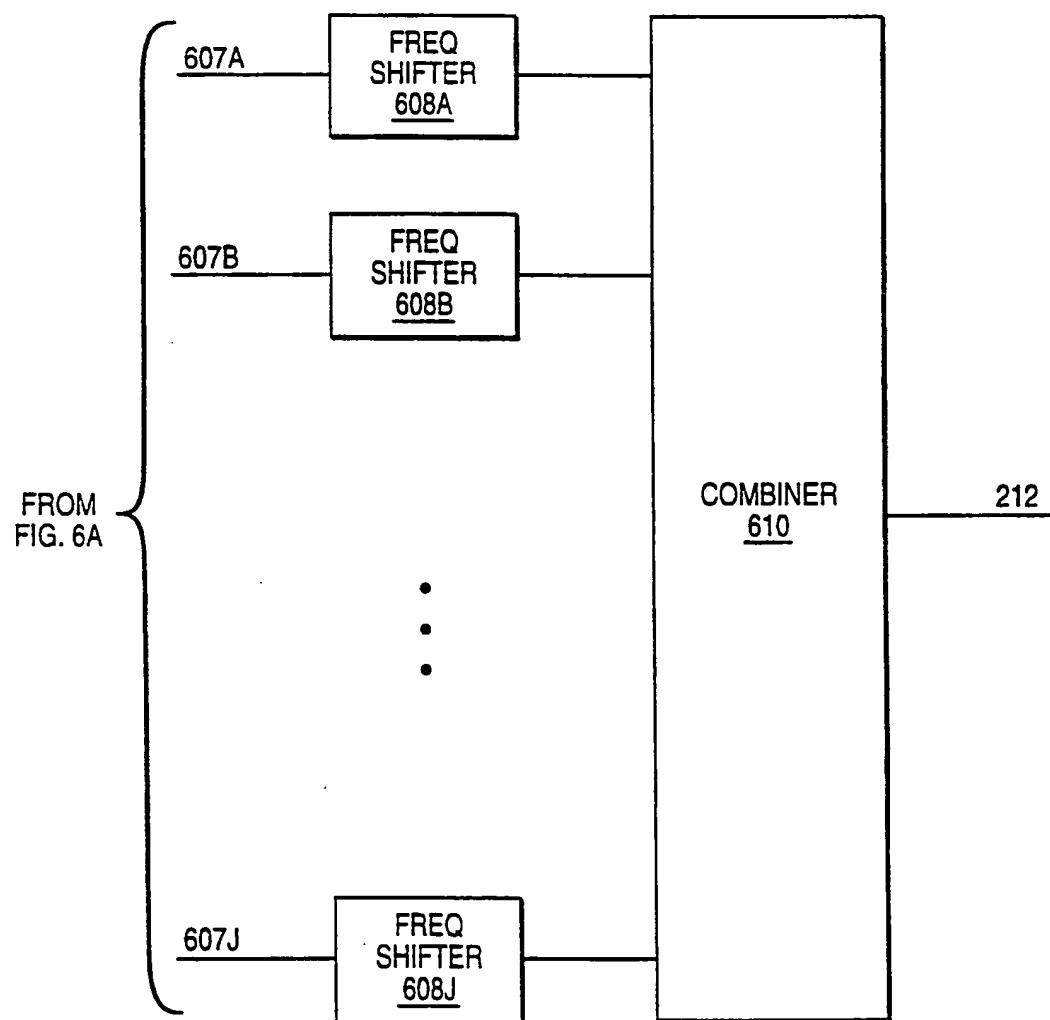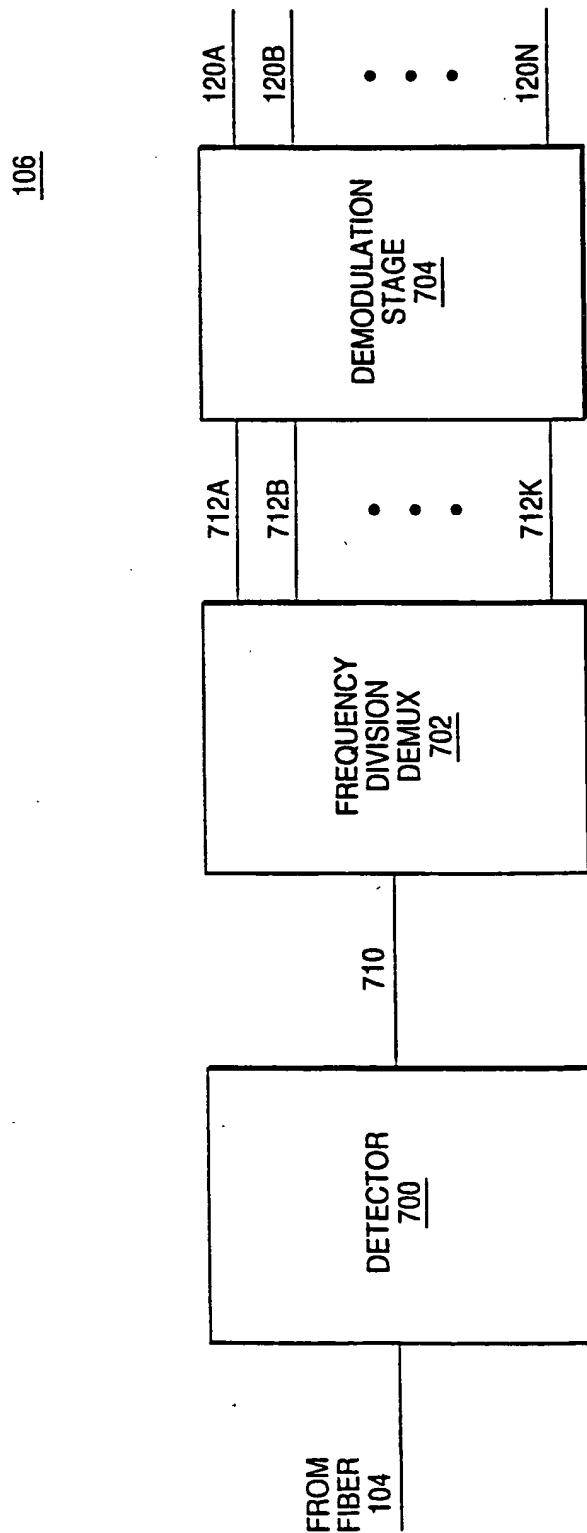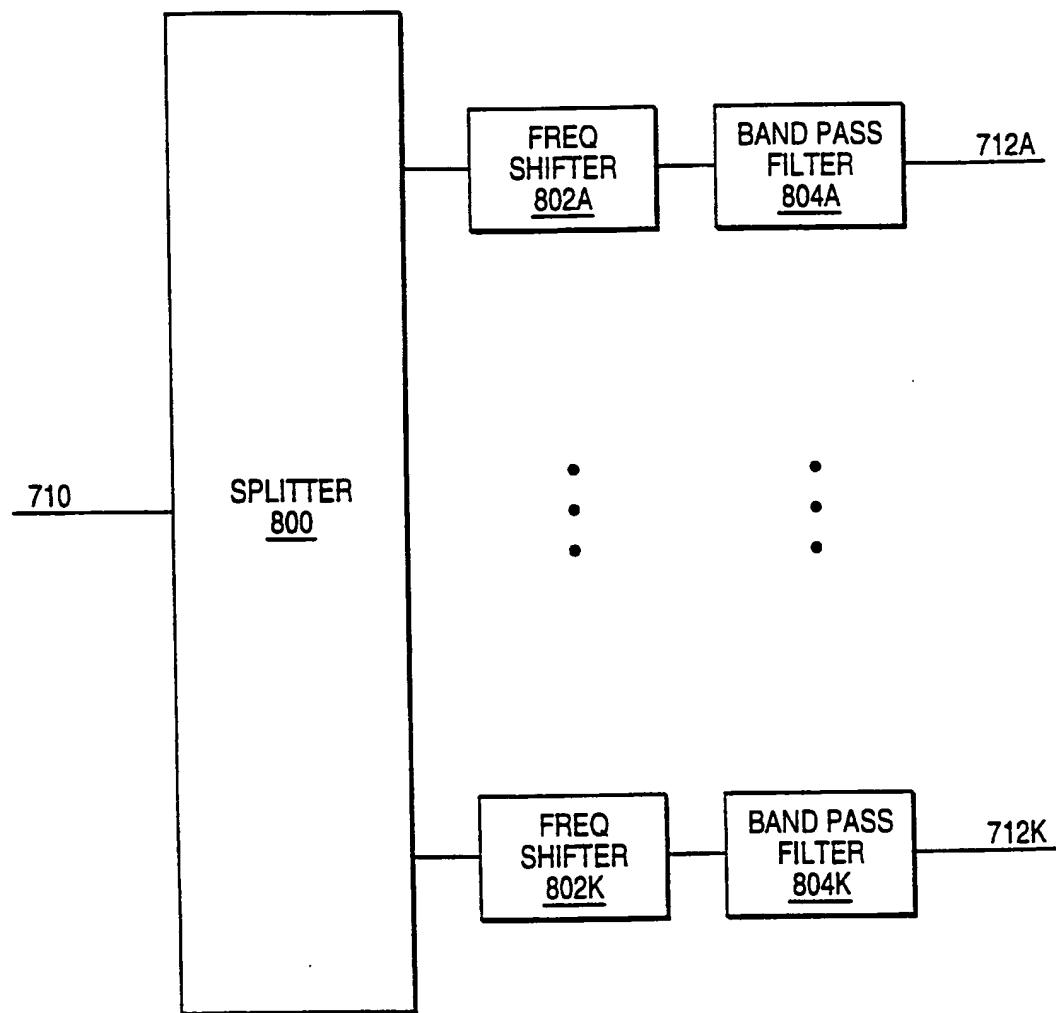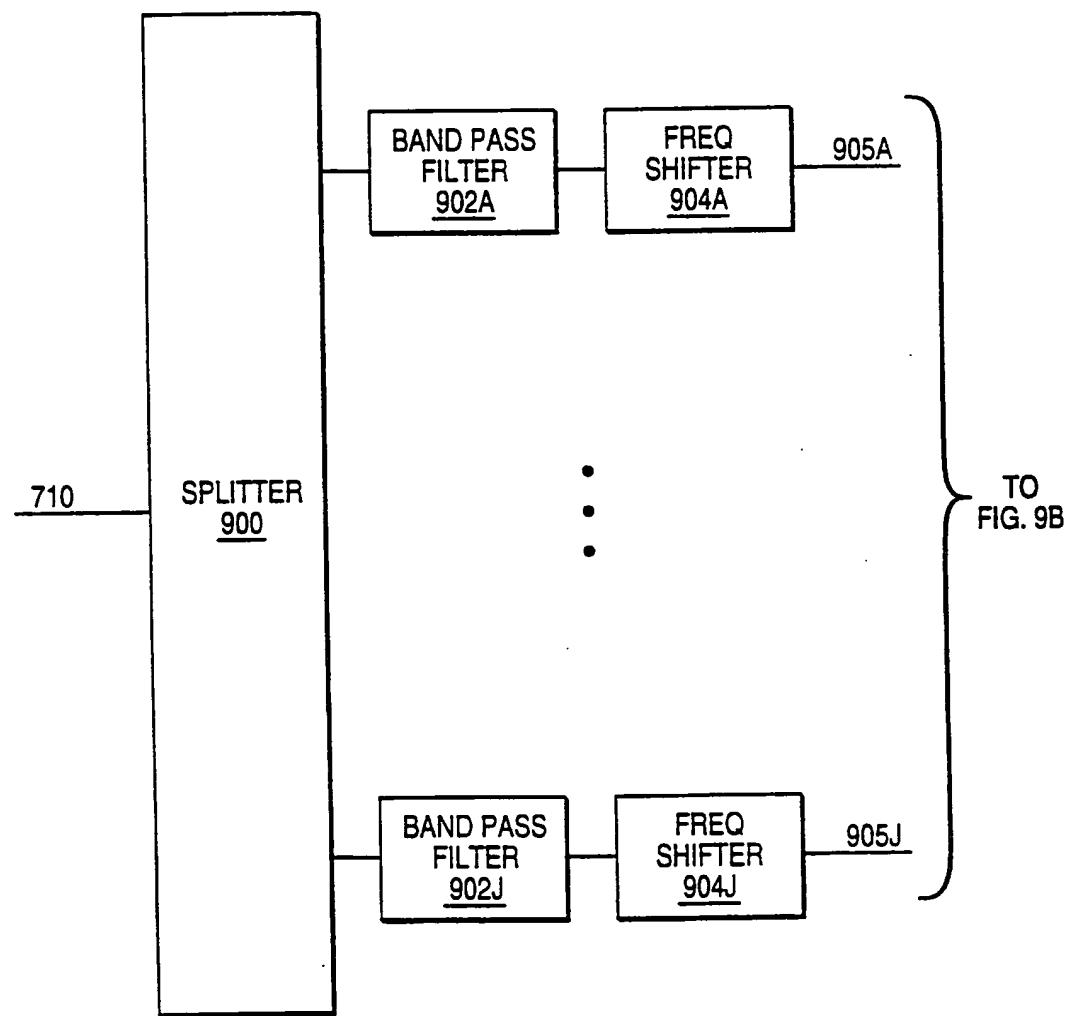

FIG. 9A
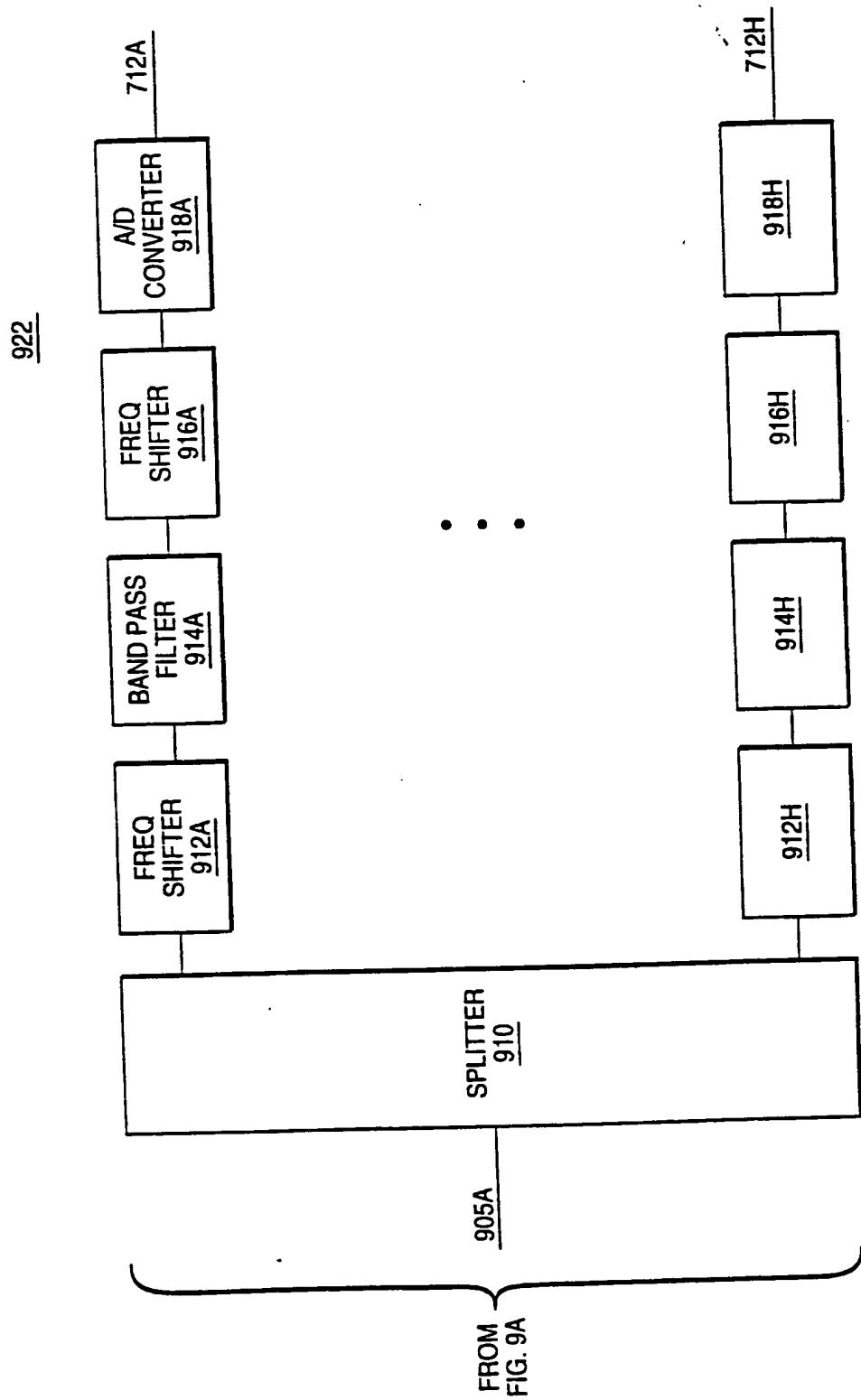
FIG. 9B

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704
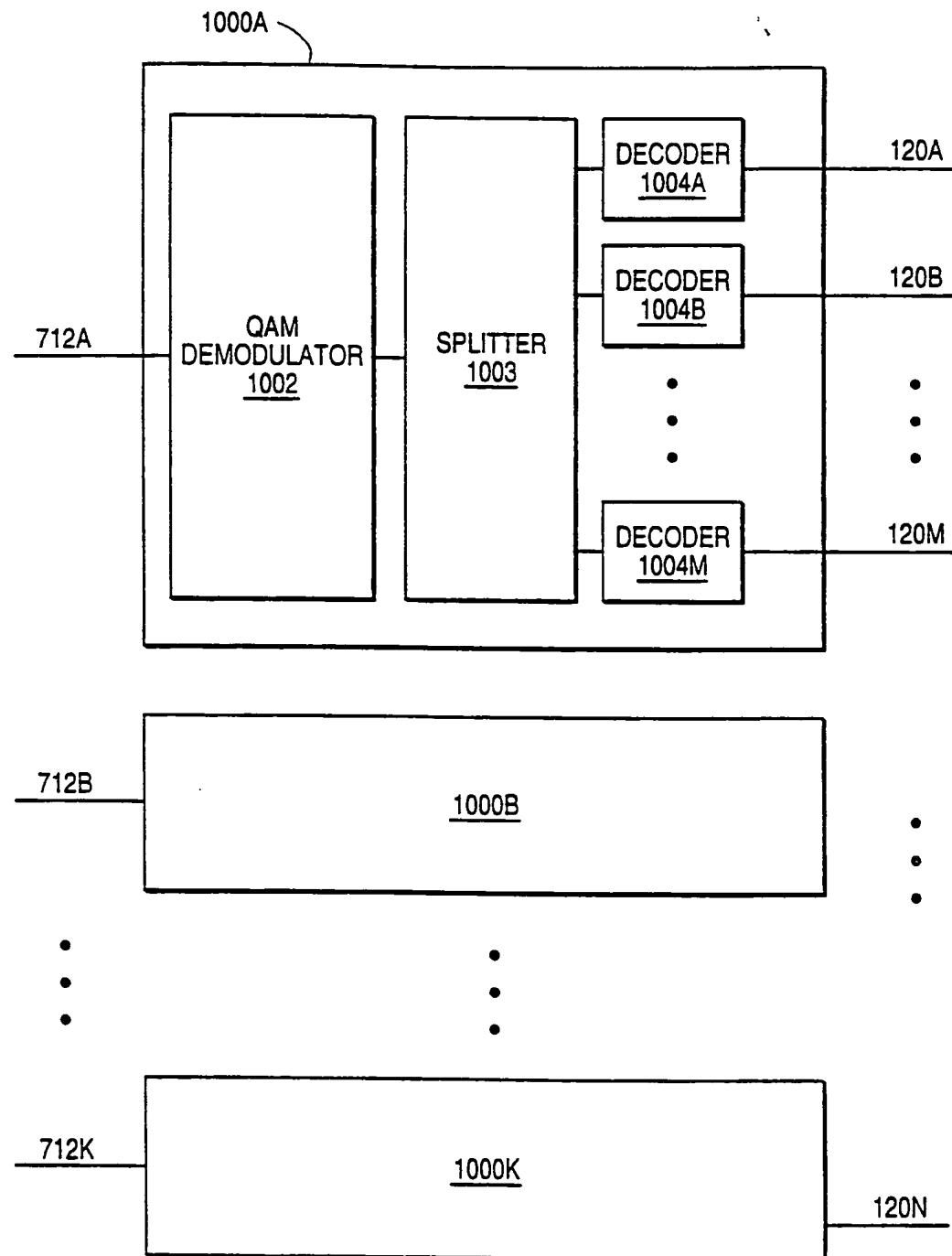
FIG. 10
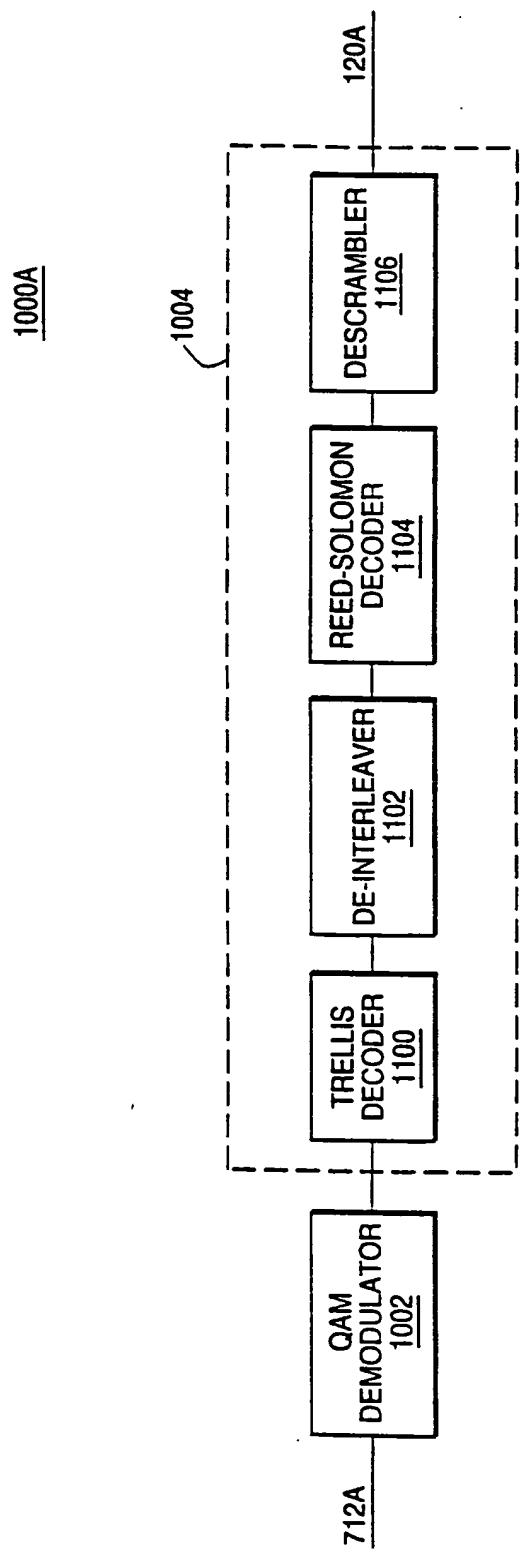
FIG. 11

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6   H04L27/34   H04L5/06   H04J14/02

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6   H04L   H04J   H04B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 387 927 A (LOOK CHRISTOPHER M ET AL) 7 February 1995 see column 1, line 45 - line 48	1-5,11, 19-23
A		6,14-18, 24,38, 46-49,55
	see column 1, line 65 - column 2, line 7 see column 2, line 14 - line 15 see column 3, line 62 - column 4, line 9 see column 5, line 9 - column 6, line 7; figures 9-11	

	-/--	

[X] Further documents are listed in the continuation of box C.   [X] Patent family members are listed in annex.

* Special categories of cited documents :

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
2 June 1999	14/06/1999

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Roldán Andrade, J

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Y	WILSON G: "Capacity of QAM SCM systems utilising optically linearised Mach-Zehnder modulator as transmitter" ELECTRONICS LETTERS, 10 DEC. 1998, IEE, UK, vol. 34, no. 25, pages 2372-2374, XP002104230 ISSN 0013-5194 see page 2372, right-hand column, line 1 - page 2373, left-hand column, line 10; table 1 ---	6,24,38, 55
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3

Inta   ional Application No

PCT/US 99/02243

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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
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A	KEANG-PO HO ET AL: "Hybrid WDM digital trunking system for both HFC and FTTC access networks" DIGEST. IEEE/LEOS 1996 SUMMER TOPICAL MEETINGS. ADVANCED APPLICATIONS OF LASERS IN MATERIALS PROCESSING;BROADBAND OPTICAL NETWORKS - ENABLING TECHNOLOGIES AND APPLICATIONS; SMART PIXELS; OPTICAL MEMS AND THEIR APPLICATIONS (CAT. NO.96TH8164), DIGEST , pages 37-38, XP002104231 ISBN 0-7803-3175-3, 1996, New York, NY, USA, IEEE, USA see page 37, line 5 - line 10 see page 37, line 31 - line 36; figure 1 ---	6,15,17, 38,48
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INTERNATIONAL SEARCH REPORT

Inte   ..onai Application No

PCT/US 99/02243

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